

Review

Exploring the key technologies and applications of 6G wireless communication network

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SUMMARY

The contemporary mobile communication has undergone a significant shift toward a novel phase characterized by the emergence of beyond 5G (B5G) and 6G technologies. These advancements underscore a focus on enhanced spectral efficiency, minimized latency, and expansive connectivity. This paper thoroughly examines 6G wireless communication networks, including their architectural framework, key technologies, application scenarios, use cases, and challenges. The architectural blueprint of 6G networks integrates space, terrestrial, aerial, and undersea communications to facilitate deep connectivity across various scenarios, which is to meet the increasing future communication requisites. Toward this end, the paper proposes 15 key technologies such as terahertz communication, visible light communication, dynamic spectrum sharing, ultra-massive multiple-input multiple-output (MIMO), and in-band full-duplex. Furthermore, typical scenarios and emerging use cases of 6G are detailed. Conclusively, this paper expounds upon potential challenges in developing and suggests the corresponding solutions, fostering a global dialogue on this transformative technological frontier.

INTRODUCTION

With the widespread implementation and adoption of 5G technology, there is a growing curiosity and expectation regarding the subsequent iteration of mobile communication technology.^{1,2} The surge in wireless data traffic is attributed to continuous advancements in intelligent emerging technologies. Projections by the International Telecommunication Union (ITU) suggest that by 2030, the demand for data traffic will escalate by a factor of 100 compared to present levels. However, the existing network infrastructure is grappling to adequately accommodate this incessantly rising demand for wireless data traffic.³ To effectively accommodate the disruptive technological transformations anticipated by 2030 and beyond, there exists a pressing imperative to develop enhanced functionalities and bolster network performance.

The goal of 6G is to explore innovative communication mechanisms that transcend the limitations imposed by current network paradigms and technologies. It integrates entirely novel concepts, architectures, protocols, and solutions designed to accommodate both existing and prospective scenarios. In response to challenges, such as network capacity constraints, energy consumption, and concerns surrounding security and privacy, 6G introduces a suite of technologies including terahertz (THz), ultra-massive multiple-input multiple-output (UM-MIMO), integrated sensing and communication (ISAC), and quantum communication (QC). The integration of these emerging technologies is anticipated to yield significant enhancements in the net-

work's key performance indicators (KPIs). A comparative analysis of KPIs between 5G and 6G, as presented in Table 1, underscores the projected advancements associated with 6G. Relative to its predecessor, 6G is poised to realize substantial increases across various metrics: network capacity is anticipated to surge by up to 100 times, while data rate, connection density, and energy efficiency (EE) are projected to experience up to a 10-fold improvement. Moreover, spectral efficiency is expected to increase by a factor of five, mobility is anticipated to double, and latency is envisioned to plummet to less than 1 ms. Furthermore, 6G holds the potential to markedly enhance coverage, reliability, and sensing/location accuracy. Specifically, it is expected to elevate coverage from 70% to 99%, enhance reliability from 99.9% to 99.999%, and elevate sensing/location accuracy from the current "meter level" to "centimeter level".

The exploration of 6G networks remains in its early phase, underscoring the imperative of actively advocating for open technological exploration and experimentation to enrich the prospects within the future communication landscape. Thus, a substantial corpus of literature has scrutinized prospective applications and resolutions for 6G systems. An overview of the 6G vision and its developmental trajectory is presented in the study by Zhang et al.⁴ Concurrently,^{5–7} delineate envisaged employment scenarios, deployment modalities, and performance prerequisites for 6G networks. Moreover,⁸ deliberate on novel network architectures, whereas^{9,10} delve into potential KPIs for 6G systems, elucidating both the conceptualization and the requisite enabling technologies for their attainment. This paper



Table 1. Comparison of 5G and 6G KPIs

KPIs	5G	6G	Enhancement
peak data rate	0.2 Tb/s	1 Tb/s	50 x
user experienced data rate	100 Mbps	10 Gbps	100 x
latency	1 ms	0.1 ms	10 x
spectral efficiency	30 bps/Hz	100 bps/Hz	> 3 x
energy efficiency	107 bit/J	109 bit/J	100 x
connection density	106 devices/km ²	108 devices/km ²	100 x
coverage percent	0.70	> 0.99	> 1.3 x
positioning precision	1 m	10 cm	10 x
reliability	0.999	0.99999	≥ 100 x

directs its focus toward fifteen pivotal technologies pertinent to 6G, encompassing facets, such as THz communication, visible light communications (VLC), dynamic spectrum sharing (DSS), UM-MIMO, and orbital angular momentum (OAM), among others. Detailed explications are provided regarding the prospective key technologies, typical scenarios, use cases, technical challenges, and plausible remedies envisioned within the realm of 6G networks.

The contribution of this paper can be briefly outlined as follows:

- (1) Anticipating the architectural framework of 6G: The paper outlines the significance of the vision and trends underpinning the evolution of 6G, while underscoring the key requirements thereof. Additionally, it offers informed perspectives and prognostications regarding the architectural blueprint of 6G networks.
- (2) Exploring key technologies: This paper analyzes the prospective advancements envisioned for 6G technology to align with the exigencies of burgeoning applications.
- (3) Addressing emerging applications: This paper provides an elaborate exposition of the five typical scenarios envisioned for 6G. The emergence of novel scenarios engenders new utilization instances, with a particular emphasis on explaining how forthcoming 6G network functionalities can effectively support these cases.
- (4) Challenges and solutions: the paper discusses technical challenges and the corresponding solutions to attain 6G goals.

The subsequent sections of this paper are structured as follows: [6G network architecture and key technologies](#) furnishes an exposition of the network architecture pertinent to 6G technology, with a specific emphasis on the key technologies envisioned to facilitate 6G systems. [Typical scenarios and use cases for 6G](#) elaborates on typical scenarios and utilization instances anticipated within the 6G framework. [Challenges and solutions](#)

[for 6G](#) discusses the technical challenges and the corresponding solutions imperative for the realization of 6G objectives. Lastly, a [conclusion](#) of the paper was provided.

6G NETWORK ARCHITECTURE AND KEY TECHNOLOGIES

Network architecture for 6G

The vision of the 6G network is to facilitate access to both virtual and real worlds, achieve ubiquitous intelligence, and offer seamless coverage to global users. The network architecture serves as the cornerstone for actualizing the vision and meeting the requirements of 6G. 6G aims to optimize the space-air-ground-sea network infrastructure by integrating terrestrial and non-terrestrial networks. The objective is to establish a comprehensive space-aerial-ground-sea integrated network (SAGSIN) with limitless coverage.⁴ However, this high degree of integration also poses complex security challenges that necessitate in-depth security impact analysis during design and deployment. As shown in [Figure 1](#), the space-air-ground-sea network consists of four segments, including space network, air network, ground network, and sea network, respectively. These segments process data independently or transmit information cooperatively with each other, which can achieve high-quality data communication and provide users with flexible end-to-end services.¹¹

Space-aerial-ground-sea integrated network

(1) Space networks

The space network consists of diverse types of satellites, constellations, and the corresponding ground infrastructures, including the ground stations and the control centers. Among them, low-orbit satellites will be an important part of space networks,¹² with advantages such as low latency, low link loss, high bandwidth, and high performance. However, space networks face security threats such as satellite signals are susceptible to interference and channels are susceptible to eavesdropping. Combined with the large-scale MIMO technology, the satellite channel characteristics are deeply analyzed to provide a low-complexity channel estimation method for the low-orbit satellite channel, and the corresponding security mechanism needs to be developed to safeguard the confidentiality and integrity of the communication.

(2) Aerial networks

The aerial network communication system is composed of a high-altitude platform (HAP) and low-altitude platform (LAP), such as airships, hydrogen balloons, aircrafts, and UAVs.¹³ Air networks are more flexible than satellite networks at high altitude due to being in the low altitude range, and have shorter response time for information communication, lower cost for base station setup, and can be used as a relay station to assist ground stations and ocean stations for communication. Utilizing an antenna base station on the UAV platform enables efficient information interaction with multiple ground users.¹⁴ As the UAV communication network has characteristics, such as short response time, high throughput, high line-of-sight transmission reliability, high mobility, and flexibility. It is used for military and civilian

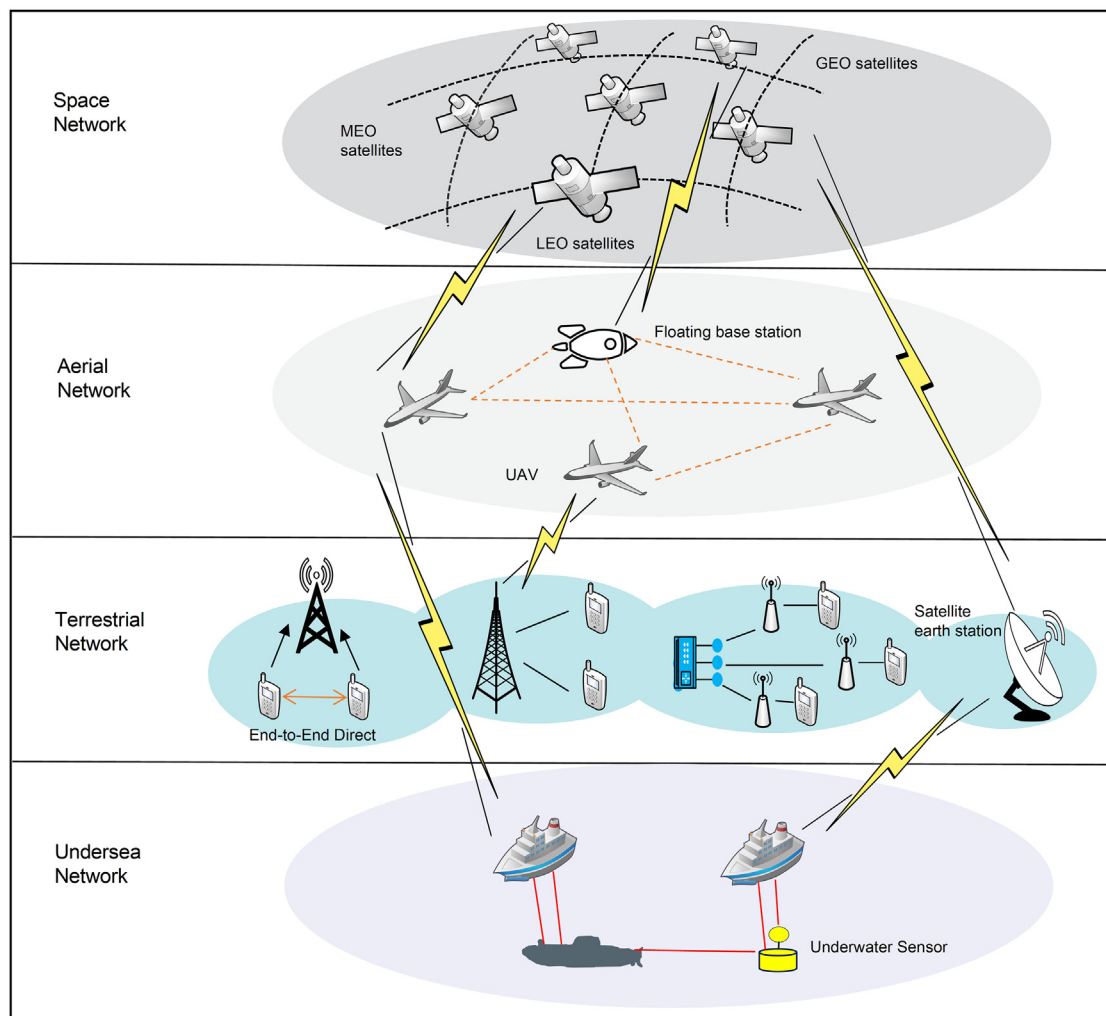


Figure 1. Displays an integrated network architecture for space-aerial-ground-sea network

The 6G network architecture includes four parts: space-based networks, aerial networks, ground-based networks, and maritime networks.

applications such as ground target detection,¹⁵ rescue and search operations,¹⁶ and disaster monitoring.¹⁷ Moreover, the topology alters frequently¹⁸ because of higher UAVs mobility, it is necessary to design an effective coordination mechanism so as to ensure the network security, providing high throughput and low latency network access for ground users.

(3) Terrestrial networks

The terrestrial network comprises components such as cellular wireless networks, satellite ground stations, ground data processing centers, ground stations, and ground internet of vehicles. Ground networks are susceptible to natural disasters and human damage, while base station deployment costs are high and coverage is limited. In order to solve the channel interference problem in the sky-earth converged network, interference suppression communication techniques have been studied,¹⁹ and a resource minimization allocation scheme has been proposed to achieve efficient resource utilization.²⁰ At the

same time, security measures for terrestrial networks, including intrusion detection, firewall and encryption techniques, need to be considered to guarantee the security of end-to-end communications.

(4) Undersea networks

The undersea network primarily comprises vessels, buoys, unmanned surface vessels (USVs), and underwater fixed sensors.²¹ Sea networks face unique challenges such as signal fading for underwater communications and uncertainty in the marine environment. To cope with these challenges, communication models designed for sea-based networks have been developed²² to cope with the large number of users and the complex and changing environment in maritime communications. In addition, the security issues of sea networks should not be ignored, and corresponding security measures, such as underwater encrypted communication and node authentication, need to be taken.

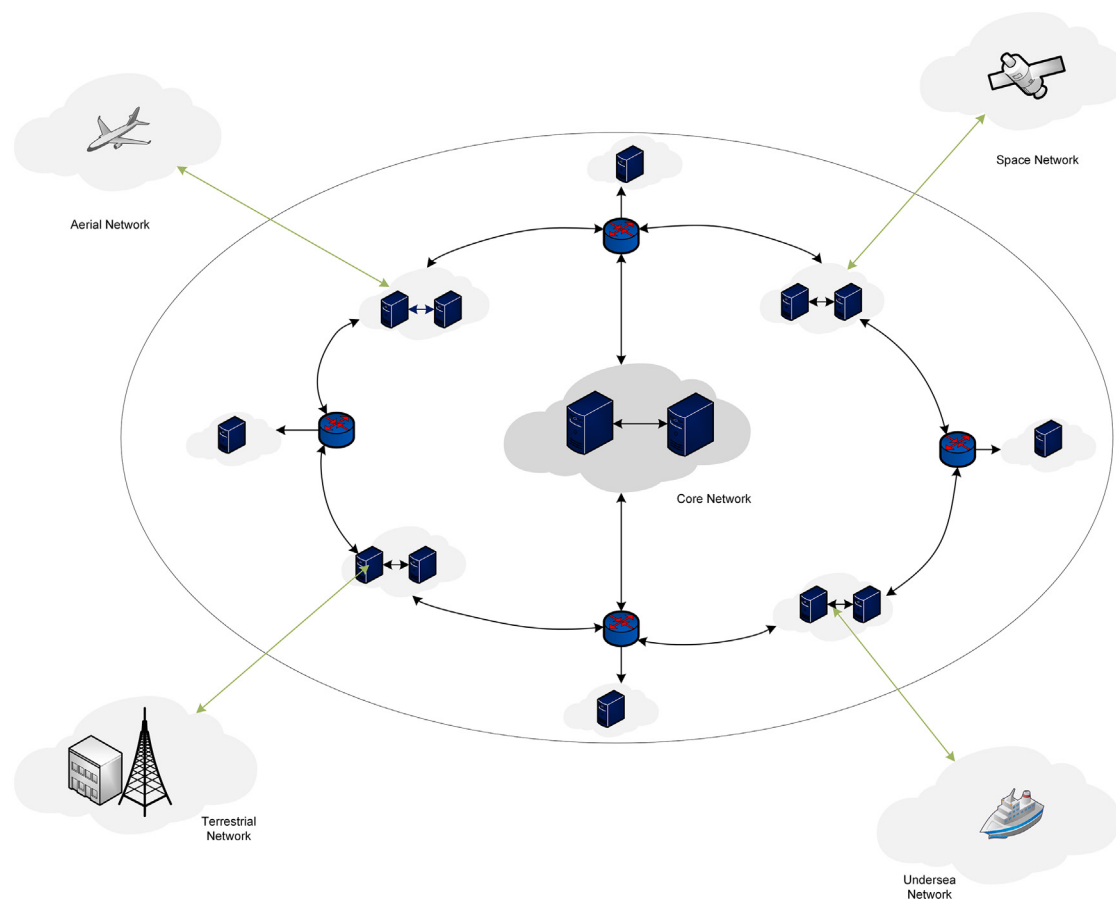


Figure 2. Unified access CN

The diagram illustrates an all-encompassing integrated communication network architecture, which is composed of aerial, space, terrestrial, and underwater networks interconnected through a core network to enable cross-domain data transmission and interaction.

Architecture design and optimization

(1) Safety design

In SAGSIN, the need for security and consistency in data transmission across network layers urgently requires the development of compatible and effective security protocols. The wide coverage and large connectivity characteristics of satellite communications and its open environment expose information transmission to serious eavesdropping and interference risks. In order to reduce the interference to satellite users, it can be realized through information exchange and beam forming technology. At the same time, star-ground spectrum sharing technology allows the utilization of security mechanisms of terrestrial networks to strengthen the security of satellite communications. Artificial noise techniques provide a new approach to strengthen the security of 6G star-ground fusion networks²³ by adding noise during information transmission to deteriorate the channel environment for eavesdroppers while controlling the interference to legitimate users. Together, these techniques and strategies provide the SAGSIN to achieve end-to-end security.

(2) Simplified design

The 5G experience has shown that complex core networks, large numbers of base stations, and a single form factor base station lead to high costs and management difficulties that significantly constrain network evolution. Therefore, in 6G design, it is necessary to sort out these issues and create a more simplified system. First, for the three-dimensional coverage needs of space-aerial-ground-sea, there is a need to unify the management of homogeneous and heterogeneous networks, thus realizing a kind of cascading omnidirectional integrated network. At the same time, by greatly simplifying signaling, protocols, and architectures, a lightweight wireless network is constructed, which not only provides a consistent user experience, but also maximizes the use of network resources and ensures service continuity. Traditionally, the use of different networks and the introduction of interoperability in order to support different scenarios has resulted in quality of service (QoS) guarantees being compromised due to differences in protocols and access mechanisms, and users may lose or degrade services when traveling across networks. Therefore, future network architectures should integrate a unified core network (CN), enabling a single CN to simultaneously connect multiple radio access technologies (RATs) for seamless switching. The network architecture shown in [Figure 2](#)

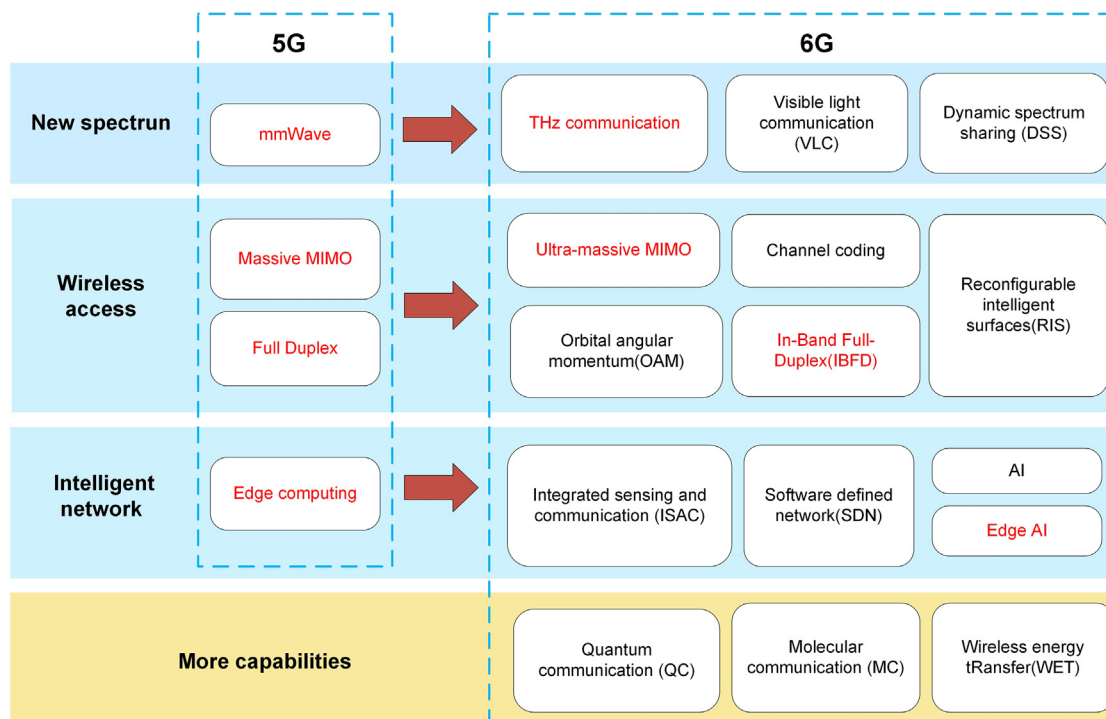


Figure 3. Key technologies for 6G mobile communication networks

It compares the key technologies used in 5G and 6G, with 6G further evolving and expanding upon the technologies of 5G.

is an example of a future network architecture that is simplified by a unified CN. By converging radio access technology (RAT) and the unified access mechanism, a CN can be connected to different RATs, enabling seamless switching between different RATs.

Second, the simplified network also needs to enhance the efficiency of mobility management and service access through unified signaling control. Turning on database stations on demand can effectively reduce the number of concurrent service base stations, lowering network costs and energy consumption while improving user experience and data transmission performance. Through cloud-based baseband processing technology, dynamic sharing and on-demand scheduling of baseband resources are realized, further reducing the overall deployment cost of the network. In addition, the plug-and-play deployment capability of the base station is crucial. This capability allows for flexible network expansion based on demand, especially in areas where there is a sudden increase in service demand, allowing for rapid provision of coverage. In this way, the construction of the network and its actual use can be closely integrated, significantly reducing unnecessary infrastructure investment and thus easing the pressure on the environment to a certain extent.

Finally, in the design and deployment of these new infrastructures, it is important to consider the impact on the ecosystem, such as waste management, energy consumption and its carbon footprint during operation. It is possible to mitigate these impacts to some extent through the use of more environmentally friendly materials and renewable energy sources. At the same time, the establishment of sound environmental assessment mechanisms

will help to identify potential environmental risks at the early stages of a project, leading to more responsible decision-making.

6G key technologies

The objective of 6G is to enhance communication systems by amalgamating communication, sensing, computing, and security functionalities, thereby furnishing intelligent services on a global scale. To realize this overarching vision, the integration of a suite of disruptive new technologies into the 6G framework is imperative. Drawing from extant research and the latest advancements in pertinent domains, we identify 16 prospective key technologies for 6G, which are classified into four evolutionary trajectories, as illustrated in Figure 3.

New spectrum resource technologies

(1) THz

THz waves represent a segment of the electromagnetic spectrum characterized by high frequencies, typically ranging from 10^{11} Hz to 10^{13} Hz, thus situated between millimeter waves and infrared radiation, hence colloquially referred to as “submillimeter waves”. THz waves are distinguished by their high frequency, broad bandwidth, substantial path loss, pronounced molecular absorption, prevalent diffuse scattering, and exceptionally narrow beam.²⁴ Relative to millimeter waves, THz waves offer greater transmission bandwidth and more advantageous propagation characteristics than infrared radiation. Despite being yet to realize practical applications, THz technology is hailed as one of the most promising innovations for 6G due to its potential to robustly support ultra-high data rate services.²⁵

The THz communication system holds the potential to facilitate high data rate communication services across diverse environments, spanning from indoor to outdoor settings. These services include HD holographic video conferences, virtual reality (VR) techniques, vehicle-to-vehicle (V2V) communications, wireless fronthaul and backhaul links, and applications such as inter-satellite communications.²⁵ Due to its short wavelength, high directionality of the link, and diminutive antenna aperture, THz technology exhibits reduced susceptibility to free-space diffraction effects, thereby offering potential enhancements in communication security.²⁶

(2) VLC

VLC involves the transmission of information by modulating the visible light spectrum, typically spanning wavelengths from 360 to 760 nm, which are commonly used for illumination purposes. In VLC, the information signal is superimposed on light emitting diode (LED) lights. This technology enables the provision of communication services in tandem with illumination and can also serve as an energy source. For instance, solar cells can be employed for simultaneous energy harvesting and high-speed data reception.²⁷ This integrated approach is environmentally sustainable, as it obviates the need for separate sources for illumination and communication network connectivity, aligning with “green” principles.

VLC holds significant potential for various applications, including indoor, underwater, and vehicular communications, as well as localization systems. In a study referenced as,²⁸ ultra-fast organic light-emitting diodes (OLEDs) were engineered with bandwidth capabilities reaching hundreds of megahertz, and subsequently implemented in a VLC system. This endeavor resulted in the attainment of data rates exceeding 1 gigabit per second.

In a study cited as,²⁹ an assessment of the performance of VLC based vehicle-to-vehicle (V2V) systems was undertaken. The findings indicated that a data rate of 50 megabits per second (Mbps) could be attained with a separation distance of 70 m between vehicles, contingent upon the positioning of the headlights. Additionally, the research documented in the study by Uysal et al.³⁰ and³¹ offers a comprehensive examination of various localization techniques for VLC-based localization. These techniques encompass received signal strength, angle of arrival, time-of-arrival, and time-difference-of-arrival.

(3) DSS

To address the scarcity of spectrum resources, there is a necessity to enhance the efficiency of utilizing the constrained spectrum, while concurrently investigating the untapped spectrum at elevated frequencies.²⁴ DSS offers a more adaptable strategy by implementing a hierarchical access structure comprising primary users (PUs) and secondary users (SUs).³² In instances where the PUs can withstand tolerable interference, the SUs are granted access to the licensed spectrum. DSS is deemed as a pivotal approach for enhancing the spectral efficiency (SE) and EE of 6G communication systems.³³

In recent years, DSS has emerged as a prominent area of research activity. Sharma et al.³⁴ stated that DSS holds potential for enhancing spectrum utilization efficiency. Naparstek and Cohen³⁵ introduced a distributed dynamic spectrum access tech-

nique grounded in deep Q-learning principles. Moreover, the integration of blockchain technology into DSS is anticipated to enhance distribution, security, and automation, while artificial intelligence (AI) is poised to elevate the efficacy of pattern recognition and decision-making processes within DSS.³⁶

Wireless access technologies

(1) Ultra-massive MIMO

When the number of antennas allocated to each user reaches several hundred or even thousands, it qualifies as UM-MIMO, representing an advanced iteration of massive MIMO.³⁷ UM-MIMO demonstrates the potential to achieve heightened SE and EE, broader and more adaptable network coverage, and enhanced accuracy in positioning across a wider frequency spectrum. It is anticipated that UM-MIMO will yield a 10-fold increase in spectral efficiency for 6G systems.⁷ Through dynamic manipulation of the wireless environment employing thousands of antennas, reconfigurable intelligent surfaces (RIS) can notably enhance network coverage, multi-user capacity, and signal strength.³⁸ Furthermore, scaling up the antenna array facilitates extremely high spatial resolution, thereby enabling precise three-dimensional (3D) localization.

(2) OAM

OAM, a form of angular momentum inherent in electromagnetic waves, arises from microscopic particles executing circular motion along the propagation axis. This motion is contingent upon the spatial arrangement of the particles and, at a macroscopic level, manifests as a vortex beam transporting the wavefront phase factor $\exp(il\phi)$ (where l represents the OAM modes and ϕ denotes the emission phase angle).³⁹ Theoretically, electromagnetic waves of identical frequencies encompass an infinite array of modes, with OAM beams bearing distinct eigenmodes being mutually orthogonal. Leveraging the orthogonal properties of diverse OAM modes holds promise for achieving heightened spectral efficiency and augmenting channel capacity without necessitating additional frequency bands.

OAM technology holds significant promise for delivering high data rate services across a range of communication modalities, including free-space optical, optical fiber, radio, and acoustic communication systems.^{40,41} Moreover, the amalgamation of OAM and MIMO communications portends enhanced capacity and spectral efficiency. In a study referenced as,⁴² an OAM-based MIMO communication system employing two OAM modes was introduced, resulting in a throughput enhancement of up to 30.50% compared to traditional MIMO configurations. Additionally, Hu et al.⁴³ proposed a time-switched orthogonal frequency-division multiplexing (OFDM)-OAM MIMO scheme, aimed at achieving exceptionally high sum rates and spectral efficiency while maintaining low computational complexity.

There is a lack of effective methods for channel measurement and modeling in OAM systems, and understanding channel characteristics is crucial for the design and optimization of OAM systems. The current research on measurement and modeling of OAM channels is still insufficient, which limits the further development of OAM technology.

(3) RIS

The implementation of RIS is predicated upon the utilization of synthetically engineered two-dimensional electromagnetic metamaterials, known as metasurfaces. These metasurfaces are comprised of a multitude of reflective elements termed meta-atoms. The electromagnetic characteristics of the metasurface are modulated by the geometric attributes of the meta-atoms (such as size, orientation, arrangement, etc.), enabling dynamic, intelligent, and independent manipulation of incident signals to achieve the desired reflected or transmitted signal, thereby augmenting wireless transmission rates. In comparison to active relay technology, RIS offers advantages such as low cost, low energy consumption, ease of deployment, real-time control of reflection coefficients to ensure reflection-free and interference-free signals, expanded signal coverage, and enhanced frequency, energy, and cost efficiency.⁴⁴

The benefits outlined above have spurred numerous researchers to incorporate RIS into traditional wireless networks with the aim of enhancing communication performance. In a study referenced as,⁴⁵ a resource allocation technique was devised for RIS-enabled downlink multiuser multiple-input-single-output (MISO) systems, aimed at optimizing the phase shift of the RIS and the transmission power in the downlink. This method yielded a potential enhancement of up to 300% in EE when compared to the utilization of conventional relays. Similarly, in,⁴⁶ system-level simulations were conducted to substantiate the assertion that RIS enhances both outdoor and indoor coverage, along with improving the ergodic rate.

(4) Channel coding

The development of channel coding, also referred to as error correcting codes (ECCs), can be traced back to Shannon's seminal contributions.⁴⁷ Over the course of the past seven decades, a plethora of ECCs have been proposed. Among these, notable examples include turbo codes, low-density parity-check (LDPC) codes,⁴⁸ and polar codes,⁴⁹ all renowned for their robust error correction capabilities and efficient decoding algorithms. Unified design of ECCs at the circuit level emerges as a pivotal technology for 6G, exemplified by advancements such as the turbo/LDPC decoder⁵⁰ and LDPC/polar decoder.⁵¹

Motivated by the imperatives of ultra-low latency and ultra-high reliability inherent in 6G communication systems, it is anticipated that shorter code lengths will be employed for ECCs. However, codes with shorter block lengths exhibit reduced reliability and pose challenges in achieving error-free transmission.⁵² To address this, optimization of the minimum block length and enhancement of robustness against transmission errors are imperative. Consequently, novel coding strategies must incorporate forward error correction techniques, which encompass innovative approaches such as new iterative retransmission schemes⁵³ and methods based on near-maximum likelihood principles.⁵⁴

(5) IBFD

Conventional wireless network design traditionally operates on the premise of half-duplex (HD) communication, wherein transmitting and receiving signals in the same frequency band are mutually exclusive activities. Contrastingly, IBFD⁵⁵ technol-

ogy permits simultaneous transmission and reception of signals within the identical frequency band, theoretically doubling spectral efficiency, extending wireless transmission capacity, and enabling more flexible and efficient network access.⁵⁶ Despite previous notions of IBFD feasibility being met with skepticism, a sequence of pioneering proof-of-concept experiments⁵⁷ has demonstrated effective mitigation of self-interference, thereby facilitating the practical implementation of this technology.

The initial documented utilization of IBFD technology in wireless communication was observed within the realm of relaying, wherein in-band repeaters are employed to enhance coverage in a wireless communication system by receiving, amplifying, and re-transmitting wireless signals within the same frequency band.⁵⁸ In a study referenced as,⁵⁸ IBFD relaying was scrutinized as a representative application. Additionally, IBFD has garnered attention for potential deployment in military jamming systems, aiming to continuously detect weak signals,⁵⁹ and provide physical layer security through intentional introduction of noise into the wireless channel.⁶⁰ Furthermore, in the study by Riihonen et al.,⁶¹ IBFD was initially introduced into radar communication systems to enable integrated communication and opportunistic wireless sensing.

Smart network technologies

(1) ISAC

ISAC stands as an enabling technology vital for the realization of integrated 6G networks, which aim to synergize communication and awareness functionalities through software and hardware resource sharing or information exchange. This synergy is directed toward enhancing the efficiency of hardware, spectrum utilization, time management, and energy consumption.⁶² As 6G technologies continue to advance, ISAC has emerged as a focal point of research, garnering significant interest and active engagement from standardization bodies and research institutions, including the ITU, Hexa-X, the Institute of Electrical and Electronics Engineers (IEEE), and the Third Generation Partnership Project (3GPP). Notably, IEEE 802.11bf was established in 2020 with a focus on wireless local area network sensing, while 3GPP SA1 initiated the ISAC research project in March 2022.

Numerous scholars have undertaken extensive theoretical design endeavors and system implementations pertaining to ISAC. For instance, Sturm Wiesbeck investigates into waveform design and signal processing for ISAC, culminating in the development of the inaugural ISAC system utilizing OFDM waveforms.⁶³ In a complementary vein, Liu et al. furnished an inclusive overview encompassing applications, current research status, and future trajectories of ISAC design.⁶⁴ Cui et al. contributed a comprehensive survey outlining advancements in ISAC, explaining its utility across internet of things (IoT) architectures, while also discussing challenges and prospects for future progress. Additionally, Shan et al.⁶⁵ proposed an ISAC solution predicated on time-modulated antenna arrays, aimed at facilitating radar-based target detection and directional communication.

(2) Software-defined networking (SDN)

In 2009, Stanford University introduced the concept of SDN, representing a novel architectural paradigm. Flexibility stands out as a fundamental requirement in the architecture of 6G

networks,⁶⁶ with SDN technology facilitating adaptable responses to diverse scenarios.⁶⁷

SDN is positioned to maintain its key role in forthcoming 6G networks, with ongoing refinement anticipated, particularly in tandem with edge computing advancements. The foundational principle of SDN entails disentangling the network's control plane from its forwarding plane, facilitating the flexible configuration and scheduling of network functions. This decoupling empowers network administrators to centrally manage and configure the entire network via a centralized controller, thereby enabling swift adaptation and realignment in response to shifts in network topology.

(3) AI

The rapid evolution of communication systems is accompanied by increasing demands and the integration of novel technologies, resulting in escalated data volumes and network intricacies. AI, distinguished by its robustness, adaptive learning capabilities, and sophisticated reasoning, presents an opportunity to imbue communication systems with intelligent management and optimization functionalities. By leveraging AI, communication networks can enhance performance and bolster the QoS.⁶⁸

AI is anticipated to find application across all layers of 6G networks. For instance, at the physical layer, AI techniques are employed in wireless channel investigations to facilitate the modeling and prediction of intricate channels, leveraging extensive datasets of propagation environment parameters.⁶⁹ In the medium access control layer, AI is extensively utilized for tasks, such as active user detection,⁷⁰ and access control mechanisms.⁷¹

(4) Edge AI

Considering the exigencies of emerging 6G networks, the prominence of connected intelligence is foreseen as essential, representing an important component thereof. Edge AI⁷² presents a nascent framework positioned to harmonize communication networks, AI capabilities, and mobile edge computing (MEC), thus furnishing a promising avenue for realizing connected intelligence. This framework facilitates the seamless orchestration of data collection, processing, transmission, and consumption at the network edge.⁷³ Projections suggest that current edge computing paradigms will evolve into edge AI technologies by the year 2030.

Edge AI holds the potential to mitigate latency, enhance privacy safeguards, and alleviate network congestion and energy consumption. For instance, MEC can ensure ultra-low transmission latency and support flawless 4k/8k video broadcasting through the computational processing of data-intensive tasks or the caching of ultra-high-definition (UHD) video content at the network edge.⁷⁴ Additionally, over-the-air federated learning (FL) offers a collaborative machine learning (ML) framework enabling the training of global statistical models across wireless networks without necessitating access to raw private data from edge devices.⁷⁵

More communication technologies

(1) QC

QC⁶⁸ is an important component of 6G communication, which utilizes the principles of quantum physics (e.g., superposition

and entanglement of quantum bits) to achieve secure encoding and transmission of data. Its unique quantum state properties provide unbreakable security for communication systems,⁷⁵ ensuring the integrity and security of information. In addition, the sensitivity of QC to interference enhances its ability to defend against external attacks,⁷⁶ and any observation of the quantum system will change its state, which can be detected by both sides of the communication.

China has built a national quantum backbone network of more than 10⁴ km, covering important regions such as Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao, and Chengdu-Chongqing, to promote the large-scale application of quantum confidential communication. In terms of satellite QC, China has successfully launched the world's first quantum science experiment satellite "Mozi", realizing satellite-to-ground QC and verifying the feasibility of global QC based on a satellite platform. Based on the successful experience of Mozi, China has also launched the Jinan-1 quantum nanosatellite, laying the foundation for the construction of a low-cost, practical quantum constellation.

(2) Molecular Communication (MC)

Drawing inspiration from natural phenomena, MC⁷⁷ represents an unconventional communication paradigm that employs molecules for encoding, transmitting, and receiving information.⁷⁸ Analogous to intercellular communication observed in living organisms, MC facilitates information transmission through the regulated release of specific molecular species, thereby enabling communication links at a microscopic scale. This concept has garnered considerable scientific interest owing to its potential to furnish distinctive communication solutions in select scenarios.

(3) Wireless energy transmission (WET)

Regarding EE, the aim of achieving a zero-energy paradigm in 6G can be substantially advanced through the integration of several key elements. These include proficient on-device smart hardware design, ultra-low-power receiver architectures, refined energy harvesting methodologies, and a zero-energy communication framework tailored for large-scale yet adaptable machine-type communication (MTC).⁷⁹ WET emerges as a compelling technology to provide sustainable power to IoT networks wirelessly, thereby curbing battery waste, streamlining maintenance and service operations, and fostering reduced emissions and enhanced deployment stability network-wide.⁸⁰

TYPICAL SCENARIOS AND USE CASES FOR 6G

Typical scenarios for 6G

In contrast to 5G communication technology, the forthcoming iteration of 6G is positioned to usher in novel application scenarios, catalyzing a significant industry advancement. While enhanced mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC), and massive machine type communication (mMTC) represent three hallmark scenarios for 5G, it is anticipated that by the year 2030 and beyond, 6G technology will broaden its application landscape beyond these

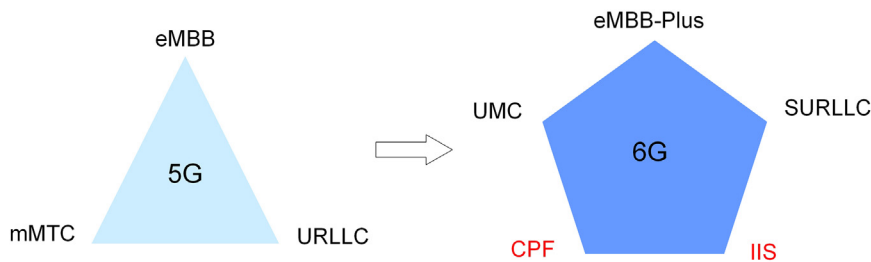


Figure 4. Typical scenarios of 6G

The evolution of typical scenarios from 5G to 6G involves the expansion of three 5G scenarios, namely eMBB, URLLC, and mMTC, into their enhanced counterparts in 6G, namely eMBB-Plus, SURLLC, and UMC. Additionally, 6G introduces two new typical scenarios, integrated intelligent services (IIS) and context-aware precision services (CPF), to further augment the capabilities of future communication systems.

foundational scenarios. Positioned as human-centric, immersive, and interactive, 6G technologies strive to cultivate an efficient and dependable IoT ecosystem. Moreover, the spectrum of services is envisaged to encompass three-dimensional coverage on a global scale. The ensuing section delineates typical scenarios envisioned for 6G.

(1) eMBB-Plus

EMBB-Plus represents the evolutionary advancement and augmentation of 5G's eMBB. eMBB-Plus introduces heightened demands for KPIs within the communication network, aiming to significantly elevate the human-centric immersive communication experience and enable global three-dimensional seamless coverage. This enhancement is poised to ensure high-quality user experiences in high-speed mobile scenarios, including those encountered aboard airplanes, ships, or high-speed railways.

(2) Secure ultra-reliable low-latency communications (SURLLC)

SURLLC represents an advancement of the capabilities seen in 5G. Its most notable application lies in telemedicine surgeries, where any latency or data loss could potentially result in surgical failure or jeopardize patient safety.

(3) Ultra-massive connectivity (UMC)

UMC will extend the capabilities established by 5G's mMTC. UMC aims to encompass a diverse array of devices deployed across scenarios such as smart cities, smart transportation, and smart manufacturing.

(4) Inclusive intelligent services (IIS)

IIS emerges as a typical scenario introduced in 6G. Leveraging the high-performance attributes inherent to the 6G network, coupled with advancements in AI, IoT, cloud computing, and other cutting-edge technologies, IIS endeavors to furnish users with high-quality, high-efficiency, high-reliability, and intelligent services.

(5) Communication perception fusion (CPF)

Another novel scenario introduced in 6G is CPF. This scenario introduces additional performance dimensions, such as high-precision positioning, heightened perception accuracy, and real-time performance, to facilitate precise location services

and environmental monitoring. Concurrently, the network must be endowed with ample bandwidth, low power consumption, robust security, privacy protection, and environmental adaptability, along with self-optimization capabilities, to accommodate the application requirements of the forthcoming intelligent society.

In summary, Figure 4 illustrates the five typical scenarios envisioned for future 6G.

Use cases for 6G

Within the typical scenarios of 6G technology, each scenario gives rise to various use cases tailored to its specific characteristics. Table 2 provides a comprehensive summary of the typical 6G scenarios alongside their corresponding use cases.

Extended reality

In extended reality (XR), as outlined by,⁸¹ virtual reality (VR) offers a completely immersive experience, wherein users engage solely with virtual objects, while augmented reality (AR) presents a hybrid experience, integrating virtual objects with both the user and the real environment. The robust bandwidth and minimal latency afforded by contemporary 5G mobile technologies have notably enhanced the VR/AR encounter for consumers. However, akin to the saturation witnessed in 4G networks due to video-over-wireless, the proliferation of AR/VR applications is poised to strain the 5G spectrum, necessitating over 1 Tb/s of system capacity, a stark departure from the 20 Gb/s target established for 5G. Moreover, to adhere to the latency requisites for real-time user interactions within immersive environments, user data rates exceeding a gigabit per second are imperative. Consequently, within 6G networks, XR will amalgamate standard URLLC with eMBB, or mobile broadband and low latency, to address these exigencies.

Holographic telepresence

Holography, as explained in the study by López et al.,⁸² denotes a method for capturing a full 3D image of an object, encapsulating all pertinent information about the object in optical formats. Holographic telepresence leverages this technique to transmit a comprehensive 3D image of an object to a distant location, enabling users to perceive the presence and intricacies of the object remotely. The advent of holographic telepresence poses significant challenges to the bandwidth and latency of forthcoming communication networks. The data rate prerequisites for 3D holographic displays, as outlined in the study by Xiao et al.,⁸³ are as follows: an unaltered hologram, devoid of any compression, featuring colors, complete parallax, and 30 frames per second (fps), necessitates a staggering 4.32 Tb/s.

Table 2. Use cases for 6G

Scenarios	Use cases	Requirements
eMBB-Plus	1. Extended reality 2. Holographic telepresence	All place higher demands on peak rate, user experience rate, system capacity, and spectrum efficiency
SURLLC	1. Industry automation and robotics 2. Autonomous vehicle 3. E health	Lower latency and higher reliability are required, with new deterministic requirements for jitter, time synchronization, and stability
UMC	Internet of everything	It supports high-precision positioning, high reliability and low-latency capabilities
IIS	Brain-computer interactions	Low latency, large capacity, and accurate sensing are required, along with privacy protection of user data
CPF	Precise positioning	Ultra-high perceptual resolution and perceptual accuracy for range, speed, angle, etc. are required

Industry automation and robotics

In recent years, the concept of industrial automation has garnered escalating interest, particularly with the evolution of Industry 4.0.⁸⁴ The forthcoming 6G technology is positioned to enhance Industry 4.0, fostering the digital metamorphosis of manufacturing through cyber-physical systems and IoT services. Robots will play key roles in real-time diagnostics, operations, monitoring, and maintenance processes in an exceedingly efficient and cost-effective manner.⁸⁵ In automated workflows, minimal latency is imperative to forestall issues that could impact systems and myriad devices. For instance, industrial control necessitates real-time operations with guaranteed microsecond latency jitter.

Autonomous vehicle

Connected autonomous vehicles (CAVs)⁸⁶ represent a vertical industry within the ambit of 6G. Autonomous vehicles embody an amalgamation of various cutting-edge technologies, including AI/ML,^{87,88} advanced sensor systems,⁸⁹ URLLC communication,⁹⁰ and high-precision location tracking.⁹¹ Notably, location precision holds great importance in the realm of autonomous driving. Leveraging the higher spectrum and shorter wavelengths afforded by 6G, CAVs can achieve enhanced sensing and positioning resolutions. Concurrently, the integration of large antenna arrays facilitates pinpoint accuracy in positioning. 6G's vehicle-to-everything (V2X) communication emerges as a potent technology for autonomous driving, furnishing requisite support for various conditions inherent to autonomous navigation.⁹² UM-MIMO downlink systems serve as key technologies within 6G V2X communication scenarios, enabling efficient communication among vehicles or between vehicles and infrastructure.

E-health

6G is set to revolutionize the healthcare sector, leveraging wireless networks to facilitate personalized care through healthcare devices and facilities. Examples include a spectrum of innovations, including smartbands,⁹³ telemedicine,⁹⁴ and drones designed for the swift transportation of pharmaceuticals and organs.⁹⁵ Smartbands enable users to monitor various physiological parameters, such as heart rate, oxygen saturation, and sleep patterns. Telemedicine transcends temporal and spatial constraints, streamlining healthcare workflows for optimized patient care. However, the efficacy of these applications hinges

on the seamless convergence of 6G location and communication technologies,⁹⁶ necessitating rigorous testing upon deployment. Moreover, given that health data ranks among the most sensitive information pertaining to individuals, privacy considerations assume paramount importance across all applications.

Internet of everything

The concept of the internet of everything (IoE) involves communication among machine-to-machine (M2M), machine-to-person (M2P), and person-to-person (P2P) interactions. Distinguishing itself from the IoT, which primarily involves wireless communication among simple physical objects like phones, computers, or home alarm systems, IoE extends communication to include processes and interactions beyond these physical entities. IoE encompasses a broader spectrum of properties compared to IoT, thus necessitating significantly higher requirements.

This use case finds applicability across diverse scenarios, including real-time monitoring of buildings, cities, environments, vehicles and transportation networks, roads, and critical infrastructure. Given the multitude of devices and processes requiring communication, IoE demands seamless connectivity and broader bandwidth. Moreover, IoE technology will prove invaluable in emergency situations, where high-speed and continuous data transmission are imperative.

Brain-computer interactions

Brain-computer interactions (BCI) involve analyzing brain signals transmitted to digital devices and interpreting them into various actions or commands. Healthcare stands to benefit significantly from BCI systems, as they enable the control of external devices like wheelchairs, prosthetics, or drones, facilitating improved integration into daily life for individuals with disabilities. With technological advancements, wireless brain-computer interfaces have become feasible. Unlike traditional BCIs, wireless BCI technology allows individuals to interact with their environment and others using discrete devices, enabling control of the environment through gestures and communication with others via haptic information. Similar to XR, wireless BCI services necessitate high data rates, ultra-low latency, and high reliability. It is evident that the KPIs provided by 6G mobile technologies are vital for brain-machine interface systems.⁹⁷

Precise positioning

In the forthcoming era of intelligent connectivity encompassing various industries, there arises a substantial need for high-precision indoor and outdoor positioning services. These services are crucial for applications such as autonomous driving, asset tracking, precision marketing, and AR. Conventional methods like satellite positioning and cellular cell multilateral positioning fall short in providing the required accuracy for these fine-grained smart services. In response, the 6G communication system will integrate multiple technologies, including ultra-broadband, UM-MIMO, ISAC, and ML. This integration aims to enhance positioning accuracy significantly, achieving an indoor positioning accuracy of 1 cm and outdoor positioning accuracy of 50 cm.⁹⁸

CHALLENGES AND SOLUTIONS FOR 6G

Key technology challenges and solutions

Challenges and solutions for new spectrum resource technologies

(1) THz communication technology aspects

THz communication, as a key technology in the field of 6G wireless communication, encounters several challenges. Foremost among these challenges is the substantial electromagnetic loss experienced in the THz band, posing a significant impediment to communication distance and transmission capacity. Within the frequency band spanning 140 GHz–350 GHz, the free space loss surpasses 100 dB even at a link distance of merely 10 m.⁹⁹ This engenders restricted cell coverage, presenting a particularly daunting obstacle for 6G application scenarios necessitating terabit-per-second (Tb/s) connection rates.

To address this problem, researchers have advanced a scheme leveraging UM-MIMO systems to augment transmission distance and counterbalance link losses through the integration of a plethora of antenna units within a confined space. Nevertheless, the realization of this scheme necessitates addressing practical constraints pertaining to energy consumption and beamforming architectures to uphold system feasibility and reliability.

Apart from grappling with high electromagnetic losses, THz communications encounter the intricacies of the propagation environment. Within the THz band, propagation contends with attenuation stemming from the resonance of water molecules,¹⁰⁰ compounded by the short wavelength that induces feeble diffraction effects and minimal sensitivity to humidity and rainfall. Moreover, challenges persist with channel fluctuations and intermittent connectivity, pivotal factors in realizing dependable and uninterrupted high-speed data transmission over THz channels.

Transmitter design plays a key role in addressing these challenges. Researchers are exploring electronics and photonics based techniques to address these challenges. Photonics approaches achieve high-speed data transmission through optical mixing and higher-order modulation with remarkable results over short distances.¹⁰¹ Electronic methods, on the other hand, enable THz signal generation in the 100–150 GHz band, with advantages in room temperature operation, small size, and ease of integration. Hybrid microwave photonics approaches combine

the advantages of photonics and electronics, offering tunability, fiber compatibility, and power handling capabilities.

(2) VLC technology aspects

VLC has experienced rapid development over the past two decades, but still faces some challenges that need to be addressed. (1) Excessive ambient light may affect the transmission of optical signals and reduce the reliability of communication. (2) VLC technology is susceptible to eavesdropping and sniffing attacks, putting network confidentiality at risk.¹⁰² (3) VLC communications are susceptible to interference from overlapping optical signals, which may lead to threats in terms of authenticity, integrity and availability. (4) The problem of optical signal reflection is also a challenge, and areas with high reflectivity can increase the vulnerability of VLC systems¹⁴⁰ and reduce the reliability of communications.

To solve these problems, researchers have proposed solutions using laser diode technology,¹⁰³ encryption and authentication techniques, advanced modulation and demodulation techniques, and optimized optical signal transmission paths. Light dimming technology offers superior brightness, efficiency, and illumination range compared to conventional LED technology, thereby reducing light interference and enhancing communication reliability. Employing encryption and authentication technologies supports the security of VLC systems against potential eavesdropping and sniffing attacks. Furthermore, the application of advanced modulation and demodulation techniques aids in minimizing optical signal overlap interference, consequently enhancing data transmission quality and efficiency. Additionally, optimizing the optical signal transmission path serves to mitigate optical signal reflection and scattering, thereby improving overall communication reliability.

(3) DSS technology aspects

DSS, despite offering the possibility of flexible use of wireless resources, has encountered multiple challenges in its implementation.¹⁰⁴ The opportunistic nature of resource usage, though enabling users to utilize idle resources, poses difficulties in ensuring QoS due to the absence of logging and charging mechanisms. Consequently, resource owners struggle to recover costs, while users may find it challenging to guarantee the required QoS. Alternatively, auction-based authorization approaches, while addressing these issues, introduce higher administrative costs.

Moreover, the implementation of DSS must confront resource allocation challenges such as spectrum awareness, access policies, and drone routing and power control. The inherent complexity and dynamics of wireless systems pose significant hurdles for traditional optimization methods to achieve these objectives.

Centralized DSS mechanisms are susceptible to trust issues, single points of failure, and center overload, posing significant challenges in ensuring fair access among heterogeneous devices in 6G networks. While numerous DSS mechanisms¹⁰⁵ have been proposed, many rely on centralized authority, limiting their security, and efficiency gains. Future research endeavors should prioritize the development of user-centered distributed

mechanisms to effectively tackle the challenges of DSS, thereby promoting secure and efficient spectrum sharing.

Wireless access technology challenges and solutions

(1) UM-MIMO technology aspects

With the rapid growth of data communication demand, although UM-MIMO is outstanding in improving spectral efficiency, its energy consumption problem is still serious, especially in the transmission, signal processing and cooling of the base station. Due to the decrease in power amplifier efficiency and increase in user equipment noise figure due to high frequency usage, although directional transmission can improve EE, the overall energy consumption still may not be reduced accordingly, but may become a new bottleneck. Therefore, to achieve sustainable deployment of UM-MIMO and related technologies, a combination of technological advances must be considered, including the development of new semiconductor materials to improve power amplifier efficiency, improved data processing techniques to cope with the demands of high data rate streams, and optimized energy management of user equipment and energy saving mechanisms on the network side.

(2) OAM aspects

Wireless communication technology based on OAM is an innovative technology that can effectively improve the spectral efficiency and anti-interference capability. A breakthrough in OAM generation, transmission, reception detection and multiplexing is required to fully utilize the tuning-to-freedom of OAM.

In particular, the most important challenge is the phase modulation and detection technology; the transmission of OAM signals relies on the precise modulation and detection of the phase, but realizing high-precision phase modulation and detection is a technical challenge. Developing new modulation and demodulation techniques is needed to achieve efficient OAM signal transmission. Further, the transmission quality of OAM signals is affected by environmental conditions such as atmospheric turbulence and multipath effects. These effects lead to shape changes and energy losses in OAM signals, which degrade the transmission quality. Therefore, anti-interference and anti-disturbance techniques need to be developed to improve the stability of the transmission quality of OAM signals. However, there are still technical bottlenecks in the accuracy and robustness of phase modulation, which may limit the practical application of OAM technology.

Eager to overcome these challenges, researchers are actively conducting related studies to promote the application of OAM technology in 6G communications. Currently, however, there is a lack of effective methods for channel measurement and modeling of OAM systems, and understanding the channel characteristics is crucial for the design and optimization of OAM systems. OAM channel measurement and modeling research is still insufficient, which limits the further development of OAM technology.

(3) RIS aspects

Currently, RIS technology encounters significant challenges across various domains including hardware realization, engi-

neering deployment, theoretical design, and control schemes/network architecture. In hardware development, RIS materials and devices are characterized by low maturity, high costs, and inadequate performance to meet demand. Engineering deployment poses challenges due to the large panel size of RIS, high wind resistance, and the requirement for substantial feeder infrastructure, limiting its practical deployment. Theoretical design aspects suffer from a deficiency in comprehensive transmission theory and system modeling, resulting in complex schemes with high overhead and limited feasibility. Moreover, control scheme and network architecture issues arise wherein RIS control impacts network design, power consumption, and deployment strategies. This necessitates careful trade-offs between power consumption and network complexity to achieve optimal performance. Addressing these challenges requires concerted research efforts and innovative solutions across multiple disciplines.

Several measures can be implemented to deal with the challenges faced by RIS technology across hardware realization, engineering deployment, theoretical design, and control schemes/network architectures. Regarding hardware realization, increased investment in research and development (R&D) for RIS materials and devices is imperative to enhance maturity and reduce costs. Additionally, efforts should focus on designing miniaturized and lightweight RIS panels to facilitate flexible deployment. Optimizing the performance of tunable devices is crucial to elevate modulation rates and diminish reflection losses for achieving extended coverage ranges. In terms of theoretical and scheme design, establishing robust evaluation frameworks for assessing system performance is essential. It is important to comprehensively account for non-ideal factors and devise feasible channel estimation and fundamental air-port transmission schemes, such as joint beamforming. Furthermore, research endeavors should explore the compatibility of RIS with sub-band scheduling schemes and enhance the speed of phase adjustment for both high- and low-frequency arrays. For control schemes and network architectures, investigations should focus on realizing passive/semi-passive and dynamic control mechanisms. Strategies need to be developed to harness performance enhancements offered by RIS in multi-bandwidth, multi-standard communication modes, necessitating the design of tailored transmission schemes. These measures collectively aim to advance RIS technology, addressing its challenges and paving the way for its widespread deployment and integration into future communication networks.

(4) Channel coding aspects

Channel coding, positioned as a fundamental technology in communication systems, has traditionally aimed to balance reliability with spectral efficiency. As we progress toward 6G, the evolution of channel coding technologies continues in alignment with this objective. However, the unique requirements of 6G necessitate a targeted approach to design and optimize coding techniques. The development of 6G coding technology demands a tailored design and optimization process to accommodate the transmission characteristics essential for terabit-rate throughput, large channel bandwidths, THz frequency bands,

and ultra-high mobility and stability inherent in complex communication scenarios. This targeted approach ensures that coding solutions are finely tuned to address the specific challenges and demands posed by 6G communication systems.

To address these challenges, several avenues of investigation can be pursued in the realm of coding techniques. First, the exploration of new high-speed coding methodologies is essential to cater to the escalating demand for higher data transmission rates. Secondly, the development of adaptive and robust coding techniques is imperative to effectively navigate through complex channel environments. Moreover, the pursuit of faster decoding coding techniques is crucial to meet the stringent low-latency requirements expected in 6G networks. Furthermore, the investigation of low-power coding techniques, along with their integration into energy-saving strategies, can significantly enhance EE in communication systems. Additionally, leveraging AI technology holds promise in discovering optimal coding modulation methods suited to the prevailing transmission environment. By employing learning, training, and search algorithms, AI can provide innovative solutions in the domain of coding technology, offering alternatives beyond traditional theoretical frameworks.

(5) IBFD aspects

In the context of 6G, IBFD communication technology confronts several formidable challenges. The development and realization of UM-MIMO arrays, along with signal processing techniques for simultaneous data transmission and reception, necessitate meticulous attention to antenna layout, connectivity, power distribution, and RF front-end design. These aspects are pivotal for ensuring the reliability and efficacy of the system. Furthermore, IBFD communication operates within a shared spectrum resource for both transmission and reception, inherently posing the challenge of self-interference management. Addressing this issue effectively is paramount for optimizing system performance. Moreover, achieving a balance between performance and energy consumption is critical for IBFD communication.

In tackling the challenges related to antenna design and signal processing, there is a pressing need for the development of advanced signal processing techniques. These should include refined antenna layout and connectivity strategies, as well as more efficient power transfer mechanisms and RF front-end designs. Additionally, to effectively mitigate interference in multi-user scenarios, the introduction of sophisticated interference coordination mechanisms is warranted to uphold communication quality among users.

(6) Energy consumption challenges and sustainable deployment strategies

Energy consumption is an increasingly prominent issue when deploying resource-intensive communication technologies, such as UM-MIMO, OAM, RIS, channel coding techniques, and IBFD. UM-MIMO relies on a large number of antennas for parallel signal transmission, which can significantly improve the spectral efficiency, but at the same time requires a large amount of power supply to maintain the normal operation of

each antenna, signal processing, and heat dissipation, which may lead to a significant increase in the energy consumption of the base station. Although OAM can theoretically achieve higher information transmission efficiency, its complex signal processing requirements and the energy consumption of dedicated hardware should not be underestimated. RIS, on the other hand, has the potential to reduce network energy consumption by optimizing signal propagation through intelligent reflective surfaces, but its effective operation also requires additional energy supply to support the drive and control of adjustable units. Therefore, the primary challenge in deploying these technologies as a whole is how to control and optimize the energy consumption level of the system while improving network performance and capacity.

In the context of pursuing sustainable development, comprehensive solutions need to be established to address the energy consumption challenges of these technologies. First, the EE of UM-MIMO and channel coding techniques is optimized by developing efficient power amplifiers and low-power coding algorithms. In addition, using AI-driven intelligent network management systems, the configuration of different technologies can be dynamically adjusted to maximize the energy management of the system. Combining the application of renewable energy sources, such as introducing green energy sources such as solar energy in the power supply of base stations and equipment, can effectively reduce the dependence on traditional power sources. In addition, a life cycle assessment should be conducted during the design phase of the system, taking into account the choice of materials for the equipment and the performance of energy consumption during operation, in order to realize a truly green communication network. Therefore, balancing performance and EE in the deployment of resource-intensive technologies and promoting the development of ICT in a sustainable manner will be an important direction for the future.

Challenges and solutions for intelligent networking technologies

(1) ISAC aspects

ISAC involves the combination of various perceptual technologies such as vision, hearing, and touch, to fuse and interact with diverse perceptual information, thereby facilitating a more comprehensive and profound perceptual experience. Amid the challenges confronting 6G networks, ISAC technology holds significant importance. Primarily, 6G networks necessitate the support of elevated data transmission rates and reduced latency, thereby imposing heightened requirements for the perceptual data transmission capability of ISAC. Furthermore, ISAC mandates enhanced computational and storage capacities for the fusion and processing of multi-source sensory data—a challenge that 6G networks must address. Moreover, the effective integration of ISAC with AI, edge computing, and other pertinent technologies is imperative to realize a more intelligent and personalized perceptual experience.

To tackle the challenges encountered by 6G networks, several strategic measures can be implemented. Firstly, advancements in wireless communication technology are imperative to achieve higher spectral efficiency and reduced transmission delay, facilitating high-fidelity sensory data transmission for ISAC.

Secondly, there is a pressing need to intensify research, development, and deployment efforts concerning pivotal technologies like edge computing and AI. These endeavors aim to bolster data processing and computational capabilities, catering to the intricate demands of multi-source sensory data fusion within ISAC applications. Furthermore, innovation in network architecture and security protocols is indispensable to foster the effective deployment and widespread adoption of ISAC technology across 6G networks. These initiatives collectively strive to enhance the overall performance, reliability, and applicability of ISAC within the evolving landscape of next-generation communication systems.

(2) SDN aspects

While SDN has reached a considerable level of maturity, it remains subject to certain constraints, particularly regarding security considerations. As 6G unfolds, it foresees a diverse array of connectivity links catering to various types of IoT devices. Nonetheless, edge IoT devices¹⁰⁶ often grapple with limitations stemming from memory and energy constraints, rendering them incapable of supporting conventional out-of-band SDN channels.

In this scenario, the adoption of in-band control emerges as a feasible solution. Nevertheless, widespread deployment still primarily relies on manual intervention, presenting a hurdle to large-scale implementations. The automated deployment of in-band control holds promise, particularly for verticals like sparsely distributed joint learning setups in smart agriculture and the local reallocation of computing resources in mobile tactical edge environments.¹⁰⁷ Simplifying the deployment process for in-band control stand to enhance the manageability, scalability, and performance of IoT devices. Within the SDN framework, the in-band paradigm stands out as a promising avenue for IoT network management within the context of 6G environments. Proper implementation thereof can facilitate more efficient and scalable management of IoT devices.¹⁰⁸

(3) AI aspects

The integration of AI into 6G networks presents various challenges, involving high computational demands, extensive big data processing, EE optimization, network security, privacy preservation, and algorithmic refinement and adaptability. To address these challenges effectively, several technical strategies can be employed. Distributed computing and edge computing methodologies can be leveraged to distribute computing tasks to the network's edge, thereby enhancing computational efficiency. Concurrently, intelligent power control, energy-efficient transmission techniques, and hardware optimization strategies can be implemented to mitigate energy consumption. Strengthening network security and privacy mechanisms is imperative to prevent unauthorized access and misuse of user data. Furthermore, continuous research and development efforts are needed to devise algorithms and models that can dynamically adapt to evolving network conditions and user requirements, facilitating intelligent network management and optimization. Through ongoing technological innovation and systematic optimization, these challenges can be

tackled, paving the way for the realization of an intelligent, high-performance, and sustainable 6G network.

(4) Edge AI aspects

Advancements in MEC platforms and enhancements in edge node computational capabilities have rendered edge AI a viable solution.¹⁰⁹ However, the direct deployment of full AI models on edge devices, devoid of any communication burden, is often impractical due to the limited hardware resources available on edge devices. One potential approach to address this challenge involves fostering collaboration among edge nodes to undertake edge AI tasks demanding intensive computation and substantial storage capacities. For instance, leveraging FL,¹¹⁰ multiple devices can collaboratively train AI models. Moreover, given that edge devices and servers must frequently exchange data and model parameters to facilitate task collaboration, model updates, and other operations, resulting in significant communication overhead, effective management and optimization of data transfers are imperative to mitigate communication costs.

Challenges and solutions for more communication technologies

(1) QC aspects

The primary application of Quantum Computing in 6G networks is to enhance network security and reliability. This is crucial due to the potential alteration and replication of quantum information, which can induce changes in the quantum state, particularly in response to quantum-based attacks. Despite advancements in Quantum Computing, particularly in quantum encryption,¹¹¹ significant challenges persist, such as operational errors and fiber attenuation. Continuous research and development of various quantum cryptography techniques, including key management, key sharing, and direct Quantum Computing security, are necessary. Additionally, Quantum Computing is well-suited for long-distance communication; however, achieving long-distance Quantum Computing on photonic platforms presents a formidable research challenge, necessitating solutions for photon loss issues, which can be addressed by segmenting large distances and employing repeaters.

However, existing repeater technologies are still in the experimental stage and have not yet been widely applied in large-scale networks, which poses a challenge to the practical deployment of quantum communications. Therefore, the maturity of these technologies and the feasibility of their practical application must be considered in future research to ensure the effective integration and diffusion of QC technologies.

(2) MC aspects

MC technology is emerging as a promising field within 6G advancements, albeit still in its early stages. Researchers acknowledge the security and privacy concerns associated with utilizing biological signals for conveying information.¹¹² Consequently, efforts have been made to devise new coding and encryption systems aimed at bolstering network security and privacy. Additionally, MC guidelines have been proposed to ensure data privacy and authentication. Bridging the gap between current research and practical applications necessitates the

Table 3. Summary of challenges and possible solutions for 6G networks

Technologies	Challenges	Possible solutions
THz	Signal transmission loss, weak diffraction effect, channel fluctuation and connection intermittency	1. Antenna design optimization 2. Photonics methods, electronics methods, hybrid microwave photonics methods
VLC	Ambient light interference, security threats, optical signal overlap interference, optical signal reflection	1. LD technology improves lighting range 2. Encryption technology to secure communications 3. Advanced modulation technology reduces optical signal overlap interference 4. Optimizing the transmission path
DSS	Designing algorithms that are integrated and reasonably intelligent	Develop user-centered distributed mechanisms to improve the security and efficiency of distributed mechanisms
UM-MIMO	Complex system design, high energy consumption and complex system management	1. Optimize antenna layout and design suitable connection scheme 2. Reduce energy consumption with energy optimization strategies
OAM	Phase modulation and detection, transmission quality stability	1. Development of new modulation and demodulation technologies 2. Research on anti-jamming and countermeasures techniques
RIS	Deployment constraints, theoretical design complexity, control schemes affect network design and power consumption	1. Designing smaller and lighter RIS panels 2. Establishment of a sound performance evaluation system 3. Study of methods for realizing passive/semi-passive and dynamic control
Channel coding	Optimized terabit rate, ultra-large channel bandwidth and energy efficiency	1. Research on new high rate coding technology 2. Development of adaptive and robust coding techniques 3. Exploring low-power coding techniques
IBFD	Signal processing, interference suppression, power and spectrum management	1. Introduction of interference coordination mechanisms 2. Optimize system design to reduce energy consumption
ISAC	High-speed data transmission, multi-source data processing, intelligent fusion	1. Strengthening R&D and application of key technologies 2. Innovate network architecture and security
SDN	Edge device resource constraints	In-band control deployment
AI	High computational requirements, energy consumption, algorithm adaptation and optimization	1. Distributed and edge computing 2. Strengthening cybersecurity and privacy protection mechanisms 3. Research and development of adaptive algorithms and models
Edge AI	Inability to deploy a full AI model, high communication overhead	1. Federated learning 2. Optimize data transfer
QC	Fiber attenuation, long-distance photon loss	1. Quantum cryptography method 2. Overcoming long distance communication problems with repeaters
MC	Security and privacy issues	Development of new encoding and encryption systems
WET	High path loss attenuation, energy beam alignment, and inefficient resource allocation	1. Beam tracking techniques 2. Multiple/hybrid radio access techniques 3. AI/ML mechanism for evaluation

development of robust and scalable technologies to establish MC networks effectively. Moreover, MC confronts research challenges in integrating biological nano-objects into the internet, representing an emerging paradigm within the field.

(3) WET aspects

WET emerges as a promising solution to power IoT devices in the 6G era. However, WET technology encounters various technical challenges, including high path loss attenuation,¹¹³ complex energy beam alignment, and inefficient resource allocation. Particularly, imperfect energy beam alignment substantially diminishes the performance of mmWave WET.¹¹⁴ Utilizing beam tracking techniques can dynamically adjust the direction and angle of the energy beam to ensure alignment performance. Addressing the path loss issue may necessitate employing mul-

ti-ple/hybrid radio access techniques. To achieve adaptive resource allocation efficiency, an AI/ML mechanism can be explored to autonomously reconfigure resources based on network, channel, and demand changes, thereby enhancing system flexibility and efficiency.

To enhance clarity, Table 3 provides a summary of the principal technical challenges and possible solutions.

Technology convergence and backward compatibility challenges and solutions

The challenge of backward compatibility stems primarily from the potentially disruptive impact of new technologies on existing network infrastructures. For example, the high-frequency band characteristics of THz communications require new antenna designs, signal processing techniques, and spectrum management

strategies, all of which may have a significant impact on existing networks. The expansion of VLC communications technology into edge computing requires compatibility with existing network architectures, including the development of new interfaces and protocols. DSS needs to build on existing spectrum utilization rules and protocols to achieve more efficient and flexible spectrum Utilization.

In order to achieve backward compatibility, the interactions between existing and emerging technologies must be fully considered. The integration of THz and VLC communications can achieve dynamic resource allocation through SDN to meet different transmission needs. The combination of DSS and UM-MIMO can optimize spectrum allocation through AI to enhance network capacity and efficiency. The combination of OAM and RIS can provide higher higher spatial reuse rate and better signal transmission path. The integration of channel coding technology with IBFD can improve system performance in noisy environments through AI-enhanced coding algorithms.

To promote compatibility, harmonized international standards and development protocol adapters are needed to ensure compatibility between old and new technologies, as well as comprehensive compatibility testing of new technologies before deployment. Adopt an incremental deployment strategy to gradually introduce new technologies to maintain continuity of existing services. On this basis, combining the flexibility of SDN and AI allows dynamic adjustment of network resources, while edge AI with quantum communications helps achieve optimized resource allocation and high security. These measures not only promote the interaction and compatibility of existing and emerging technologies, but also lay a solid foundation for the successful deployment of 6G networks.

Potential non-technical challenges and solutions

Demand and cost dilemma

The high complexity and multi-dimensional technical requirements of 6G networks make it easy to overlook the hidden costs of network upgrades and modifications, including, but not limited to, network architecture adjustments, equipment compatibility testing, increased operation and maintenance costs, and training costs for updating personnel skills. These cost factors must be fully considered at the project planning and budgeting stage to prevent funding gaps and schedule delays in project implementation. A comprehensive pre-implementation cost-benefit analysis is therefore essential to help industry players accurately identify and anticipate all relevant costs, so that a more reasonable and feasible deployment plan can be formulated.

To address this challenge, a series of concrete measures are recommended. First, industry players should establish a comprehensive cost assessment model that covers direct investment costs, long-term operating costs and potential risk costs. Second, enterprises should adopt the strategy of “building networks on demand”, prioritizing the hot spots and industry value of 6G applications, and implementing targeted network coverage instead of blindly pursuing a comprehensive expansion. In addition, cooperation among the government, industry organizations and enterprises should be promoted to jointly formulate technical standards and management specifications

to guide 6G network construction and application deployment and ensure the sustainable development of 6G technology. Through these measures, costs can be effectively controlled and economic benefits maximized while ensuring technological advancement.

Potential regulatory, ethical barriers

With the rapid development of 6G technologies, existing regulatory frameworks may not be able to effectively address the complexity and diversity of emerging technologies, leading to inadequate regulation of innovative business models and their potential impacts. This has also been significantly reflected in the development of 5G, with many countries and regions facing regulatory challenges in the implementation of 5G stemming mainly from the lagging adaptation of traditional frameworks to new technologies. For example, in the early stages of 5G deployment, the lack of clear spectrum allocation and network security standards dampened the investment enthusiasm of market participants and slowed down the pace of innovation significantly. Therefore, in order to avoid similar dilemmas in the development of 6G, it is necessary to establish a dynamic and forward-looking regulatory mechanism. Such a mechanism should be able to respond quickly to technological changes and ensure flexibility and timeliness in policy formulation. In addition, allowing the testing of new technologies in controlled environments through the introduction of pilot projects to further provide data support for their compliance and safety, as well as taking into account the views of multiple stakeholders in the policy formulation process, will help to enhance the effectiveness and adaptability of the regulatory framework, thereby creating a more favorable environment for investment and innovation.

In addition, ethical issues and public acceptance are important aspects that must be considered in the regulatory framework. With the in-depth application of 6G technologies in the areas of data collection, privacy protection and social impact, how to safeguard individual privacy, data security as well as fairness, and prevent technological abuse and social inequality will become an ethical issue that needs to be urgently addressed. To this end, it is important to establish sound data protection policies to ensure that users' informed consent and data rights are respected.

CONCLUSION

5G networks have commenced deployment across various nations and regions, offering not only accelerated mobile broadband but also expanding into novel scenarios like URLLC and mMTC. While 5G is in its early stages, researchers and developers are already probing into the exploration and experimentation of 6G technology. The sixth generation of mobile communication systems promises exceptionally high data rates and minimal latency, coupled with spectral efficiency and connectivity density 10–100 times superior to 5G. 6G networks will build upon, innovate, and advance from the emerging foundations of 5G networks, addressing their limitations while catering to the demands of evolving information services. Consequently, 6G is poised to exert a profound influence on the future landscape of mobile wireless networks.

This paper offers a thorough examination of the architecture, key technologies, use cases, and challenges encountered within

6G networks. Moreover, it examines the connections among typical scenarios, use cases, demanding prerequisites, and critical technologies. Lastly, a detailed description of the barriers and expected solutions in terms of technical and non-technical challenges is provided.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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